Is the Risk of North-South Technology Transfer Failure an Obstacle to a Cooperative Climate Change Agreement?

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Abstract

We set up a stylized model with endogenous North-South technology transfer for climate change mitigation. We theoretically identify the driving factors that enhance or hinder cooperation with socially optimal binding targets on emissions and on investment in technology transfer. We find that the risk of technology transfer failure creates an obstacle to the achievement of the cooperative agreement: Under cooperation, the South will have to fulfill the emissions target at high costs if technology transfer fails. Under non-cooperation without any binding targets, the North still has an intrinsic motivation to reduce emissions in the South at low costs via technology transfer; and the South does not have the pressure to fulfill an emissions target. As a result, non-cooperation shifts part of the costs of a technology transfer failure from the poor South to the rich North and can thus be preferable for the South. Two policy implications for achieving the cooperative solution are derived: First, the South should be insured against or compensated for a technology transfer failure. Second, an agreement on technology transfer should be formulated in terms of emissions reductions or low-carbon technology capacities that are to be achieved rather than in terms of monetary payments with uncertain effects on emissions. We discuss the model results in the context of empirical facts and current developments.

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1 Introduction

International technology transfer with the aim to reduce carbon emissions in developing countries has frequently been discussed at recent conferences on climate change (Bali, Copenhagen, Cancun, Durban, Doha). We define international technology transfer as any financial or material cross-border exchange that is associated with the cross-border diffusion of technological knowledge, more specifically, knowledge about technologies that reduce carbon emissions. We treat it as a synonym for international technology spillovers. Technology transfer is now being realized, in particular via 'green' technology funds (for example Climate Investment Funds, 2011; for an overview see Climate Funds Update, 2011).[1] In the current debate and in the framing of technology funding, the focus is clearly on transfers specified in monetary values without discussing opportunities and risks of these transfers. For example, the frequently mentioned 100 billion US-$ annually by 2020 for developing countries do not clearly specify the aim of the transfer and the way to achieve this aim. The possibility and the consequences of a technology transfer failure with respect to emissions reductions are not discussed. Therefore, the crucial question reads: Is the Risk of North-South Technology Transfer Failure an Obstacle to a Cooperative Climate Change Agreement?

The literature based on *numerical models* has shown that spillovers can strengthen the stability of climate policy coalitions: Nagashima and Dellink (2008) investigate how *exogenous* international technology spillovers affect the formation and stability of climate coalitions consisting of different countries. They find that participation in climate coalitions increases in the strength of global technology spillovers. But technology spillovers "cannot overcome the strong free-rider incentives that are present in larger coalitions". The literature on issue linkage assumes that international technology spillovers are present within a climate policy coalition but not outside the coalition. Kemfert (2004), for instance, finds that issue linkage in the form of technological cooperation has a stronger potential to enlarge a climate coalition than issue linkage in form of trade sanctions. Lessmann and Edenhofer (2011) find in their numerical model that productivity spillovers affecting overall production are more effective in increasing the coalition than spillovers specifically affecting emissions reductions. The reason is that only those in the coalition can benefit from spillovers raising overall production, while emission-specific spillovers

[1] Coninck et al. (2008) name the following four kinds of technology-oriented agreements: "(1) knowledge sharing and coordination (of knowledge transfer); (2) research, development and demonstration (RD&D); (3) technology transfer; (4) technology deployment mandates, standards, and incentives."

raise the coalition payoff but also the incentive to free-ride by outsiders. El-Sayed and Rubio (2011) study international cooperation on technological development as an alternative to international cooperation on emissions reductions in a *theoretical model*. They identify the grand coalition as a likely stable outcome if marginal damages are sufficiently strong and the scope of international technology spillovers is not very large.

A hypothesis derived from this literature can be phrased as follows: The presence of international technology transfer in the sense of technology spillovers can support a cooperative climate policy agreement. The reason is that spillovers can be more strongly exploited within the coalition, which creates an incentive for being in the coalition. Nonetheless, the coalition will be destabilized due to free-riding incentives when spillovers become too strong. However, the literature has so far not yet *theoretically* examined whether in the presence of *endogenous* North-South technology transfer a cooperative solution[2], or a non-cooperative solution[3] is more likely. We fill this gap. Different to the existing studies, we examine the driving forces (incentives) of international technology transfer in a *theoretical* framework and do not a priori assume that spillovers exist exclusively within the coalition. We then compare the theoretical outcome with stylized facts in order to decide which solution is more likely in reality.

For this purpose, we analyze and discuss a stylized model of technology-related and not-technology-related transfers from an industrialized region (North) to a developing region (South). The North can be interpreted as an aggregate of the industrialized countries willing to undertake climate action. The South can be interpreted as an aggregate of the developing countries. We set up a four-stage game. In the first stage, the North and the South decide upon their strategy, this means whether they want to cooperate or not. Cooperation implies that both, North and South, agree to a binding socially optimal emissions target for each region and a socially optimal investment in North-South technology transfer. Non-cooperation means, there is no agreement. In the second stage, the North, having advanced technologies in his repertoire, decides upon investment in technology-based abatement within the North and in the South. The North's technology-based abatement within the the South is referred to as (North-South) technology transfer, and only technology transfer is subject to uncertainty in its outcome. The outcome of technology transfer is revealed in the third stage: Technology transfer can be a failure or

[2] A North-South coalition with binding emissions targets for both regions and binding North-South technology transfer payments, maximizing *joint* consumption (centralized global social planner solution).

[3] No binding emissions targets for the South and maximizing *regional* consumption (decentralized Nash solution).

a success like in a Schumpeterian model of innovation with creative destruction (Aghion and Howitt, 1992). Thus, regions' decisions which strategy to choose in stage one are made on the basis of expected values. In the fourth stage, each region, North and South, can make use of not technology-based abatement. Thereafter, the economies will suffer climate change damages depending on the level of emissions. Reaching the same emissions reduction in the South will create higher costs in case of a technology transfer failure than in case of a success.

As a result, our model analysis combined with stylized empirical facts does not fully confirm the above hypothesis that international technology transfer supports cooperation: We find that a non-cooperative solution with North-South technology transfer is a likely outcome. North-South technology transfer is in the North's own interest to make use of cheap emissions reductions in the South. Stronger emissions reductions through technology transfer not only increase the benefit of cooperation, but also of non-cooperation, benefitting from technology transfer. And as a new aspect, we argue that stronger emissions reductions through technology transfer tighten the emissions target of the South under cooperation. This increases the pressure on the South in case of a technology transfer failure and makes cooperation less attractive. In the non-cooperative case, the risk of a technology transfer failure is mainly borne by the North, the rich region. In the cooperative case, the risk is mainly borne by the South, the poor region. Hence, taking the risk of a technology transfer failure into account, the South may refuse to sign a binding agreement on emissions targets and technology transfer payments – even when this agreement includes an inter-regional monetary transfer that would in the absence of international technology transfer or under ideal conditions of technology transfer, i.e. without the possibility of a technology transfer failure lead to cooperation. This means, the new elements that we introduce – the endogenous choice of investment in North-South technology transfer, and the uncertainty in the outcome of this investment in terms of emissions abatement – generate this result.

Our paper is structured as follows: It further reviews related studies in section 2. It sets up and solves a stylized model within a four-stage game in section 3. It concludes in section 4.

2 Literature

One important literature stream studies the formation of climate coalitions (for overviews see Carraro and Siniscalco, 1998, Finus, 2003, and Finus, 2008) focusing on international financial transfers (Carraro et al., 2006), environmental standards (Barrett, 2003, ch. 15), breakthrough technologies (Barrett, 2006), endogenous technical change (Lessmann et al., 2009; Nagashima et al., 2011), and issue linkage (Carraro and Marchiori, 2004; Kemfert, 2004). Our study, on the contrary does not look at multiple players, but focuses on the behavior of North and South in climate and technology negotiations. The North can be seen as an aggregate of the industrialized countries, and the South as an aggregate of the developing countries. Moreover, we focus on international technology transfer, which is not the main aspect of this literature stream.

A recent literature stream studies the influence of international technology diffusion on different carbon pricing schemes. Golombek and Hoel (2005) theoretically analyze non-linked/non-cooperative quotas and taxes as well as linked/cooperative quotas and taxes taking international technology spillovers into account. They find that emissions are lower under the tax than under the quota in the non-cooperative case where each country chooses a tax level. This happens because additional research and development (R&D) reduces emissions abroad via technology spillovers in the tax case but not in the quota case where emissions caps are fixed. In the case of identical countries, the non-cooperative tax case also leads to higher R&D investment and is welfare superior to the quota case. This result is not that clear-cut though in the cooperative case with a carbon price equalized across countries. Golombek and Hoel (2011) theoretically analyze different strategies of international cooperation on emissions and climate-friendly technologies taking international technology spillovers into account. They examine a four-stage game in which first the government of each country sets an R&D subsidy, second profit-maximizing firms invest in R&D, third the government sets a carbon tax, and fourth firms choose emissions stemming from their production. They show, for instance, that it is beneficial to increase the non-cooperative R&D subsidy in each country if there are positive cross-country spillovers, the domestic carbon tax is lower than the Pigovian tax (the sum of the marginal climate costs of all countries), or when the carbon tax is set internationally below the socially optimal level.

Different to the latter studies, we do not examine various carbon pricing schemes. Instead, we introduce *risk* in terms of technology transfer failure. This creates novel aspects that are practically relevant for deciding upon North-South transfers from the point of view of industrialized (Annex I) and developing (non-Annex I) countries.

3 Analysis

This section describes the overall framework, the model, the non-cooperative and the cooperative solution. It then compares the two solutions and describes and discusses the overall solution of the game. It finally confronts the results with empirical observations.

3.1 Framework

This subsection describes the overall framework of the four-stage game. We imagine a two-region world consisting of an industrialized region, the North, n, and a developing region, the South, s. We will also call them 'players' in the following. We assume a four-stage game in which the stages follow consecutively in time. Figure 1 illustrates the sequence of the game.

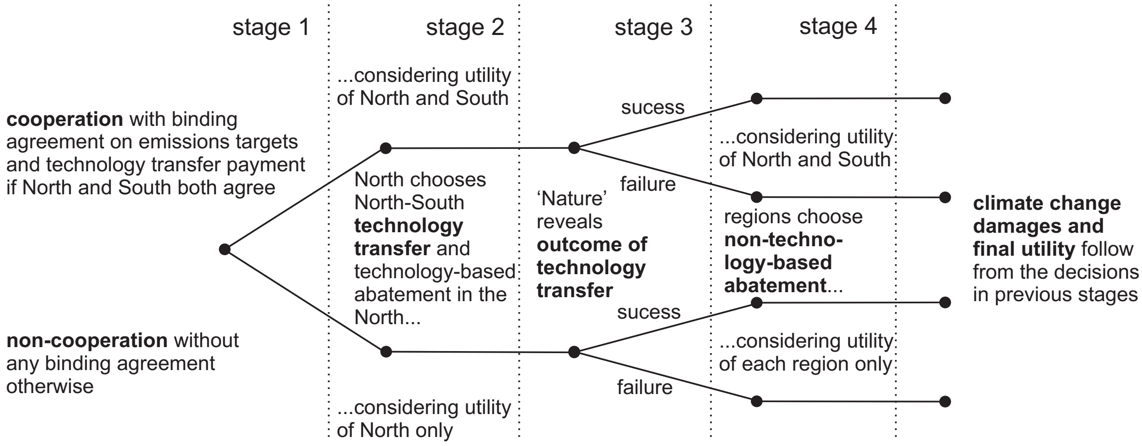

Figure 1: Sequence of the game.

In the first stage, the players decide upon their strategy: cooperation or non-cooperation. Under cooperation, the players maximize their joint utility. This results in the centralized social global optimum. The players make a cooperation agreement and adhere to it. The agreement fixes the globally optimal emissions level for each region. It also fixes the socially optimal level of North-South technology transfer. (Technology transfer will be explained in the following.) Hence, it is issue-linkage of an environmental target with a technology target. It is important to note that it is only possible to agree upon the *volume* of North-South technology transfer in form of a monetary value, while it is not possible to agree upon the *outcome* of technology transfer in terms of emissions savings. This is what has been announced at the latest Conferences of the Parties (COP): US-$100 billion annually by 2020 for mitigation in developing countries. And this is what we currently observe under the framework of technology funding schemes. As we will see later, the outcome of technology transfer is due to uncertainty and exogenously determined by 'Nature' and not influenceable by the players. This assumption is made because technology transfer in the sense of imitation is like original innovation subject to engineering and managerial restrictions and ex-ante unknown developments. A monetary transfer between regions (not associated with technology transfer) is available in the model which guarantees that both regions are better off under cooperation than under non-cooperation *under ideal conditions, i.e. given that technology transfer is successful.* This is what happens in the current debate and framing of technology funding and climate change-related transfers: Agreements refer to monetary values without discussing the possibility and the consequences of a technology transfer failure. Under non-cooperation, each player maximizes its own utility given the behavior of the other player. This results in the decentralized Nash equilibrium. Again, the outcome of technology transfer is subject to uncertainty. But now there is neither a binding agreement on emissions nor on technology transfer. Each player will choose the strategy that maximizes expected utility.

In the following stages, the economic decisions are made, given the strategy (cooperation or non-cooperation) previously decided upon by the players, i.e. the governments of each region. We look only at the macroeconomic outcome, i.e. the macroeconomic behavior of each player and not at the underlying micro-foundations like profit maximization of firms. Each player draws utility from consumption. Consumption is production net of climate change damages and net of investments in abatement. Abatement reduces carbon emissions stemming from production and thus reduces climate change damages.

In the second stage, the decision upon technology-based abatement is made. Technology-based abatement is treated as a long-term abatement option since research and development and technology diffusion are complex processes that require time. Empirical evidence (e.g. SEI, 2006; World Bank, 2008) and the current debate show that industrialized countries contribute most of the private and public research and development (R&D) in the world and have high-productivity and low-carbon technologies available that developing countries do not have. Thus, by assumption, only the North has technology-based abatement options available in our model. Technologies include physical capital and know-how embodied in this capital as well as knowledge about how to produce, use, maintain, and further develop these technologies. The North can now invest in technology-based climate abatement options in the North and in the South. We call the North's technology-based abatement within the South technology transfer.[4] The underlying formal model will be explain in the following section.

However, the outcome of technology transfer aiming at carbon emissions reductions is due to uncertainty. Similar to the assumption about innovation in a Schumpeterian model of endogenous growth, technology transfer might be successful and achieve the expected emissions reduction with a certain probability in our model, or it might fail and achieve no emissions reduction with a likelihood of one minus this probability. Hence, we look at the two extremes, complete success and complete failure. In reality, the outcome will be somewhere in between. Nonetheless, the *probability* of transfer success is known to the players so that they can calculate expected values and decide upon strategies based on these expected values. Reasons for a technology transfer failure can be technical: The transferred technologies are not as good as expected, or they cannot be adopted because of local conditions and do not diffuse through the economy, or they brake down due to lacking maintenance, malfunction, and missing spare parts after a short period of time. This means, although governments invest in technology transfer, technology transfer may fail: Institutions like the German GIZ (Deutsche Gesellschaft für Internationale Zusammenarbeit) support developing countries in terms of skills, technologies and finance. Nonetheless, many developing countries are not able to adopt these skills and technologies because they lack absorptive capacity related to education, infrastructure and the legal system.[5] Reasons for a technology transfer failure can also be behavioral: Local politicians, managers, engineers, or workers in both regions have self-interests and might not make enough effort in realizing technology transfer since they are not directly affected by long-term climate change effects. Importantly, all these reasons cannot be influenced by the players of our game, i.e. the government of the North or the government of the South. The outcome of technology transfer is thus exogenous to the players. We can think of the

[4]We define international technology transfer as any financial or material cross-border exchange that is associated with the cross-border diffusion of technological knowledge, more specifically, knowledge about technologies that reduce carbon emissions.

[5]Moreover, governments in industrialized countries make use of intellectual property rights (IPR). On the one hand, IPR enhance the incentive to engage in research and development (R&D) because they help firms reap the benefits of their R&D efforts in domestic or foreign markets. On the other hand, IPR can hinder the international diffusion of technologies because they deny firms in developing countries access to technological knowledge existing in industrialized countries. (For an overview on patents and clean energy see UNEP, EPO and ICTSD, 2010.) Hence, the effect of IPR on technology diffusion is ambiguous.

outcome as being a draw by Nature with given probability. Hence, neither player can be blamed for a technology transfer failure.

In the third stage, the outcome of technology transfer, success or failure, is revealed. As a consequence, the economic decisions of stage 2 can only be made based on expected values. The same is true for the decision upon strategies in stage 1.

In the fourth stage, the players can invest in non-technology-based abatement options within each region. This includes output reductions in order to reduce emissions as a straightforward option or better energy management. Non-technology-based abatement is in this sense treated as a short-term abatement option. It does not require technological knowledge or capabilities and is therefore equally available in both regions. But it is not a budgetary transfer that can be used for consumption. Technology-based options, on the contrary, are long-term options that are not available in this final stage. In case of a technology transfer failure, the players may want to increase their non-technology-based investment to compensate for that. In case of a technology transfer success, they may want to reduce their non-technology investment. However, technology transfer failure means that an important abatement option is not available so that the overall cost of achieving a certain emissions target rises.

3.2 Model

This subsection describes the economic model in more detail. We imagine a two-region world consisting of the industrialized region, the North, n, and the developing region, the South, s. The North can be thought of as an aggregate of the industrialized countries willing to undertake climate action. The South can be thought of as an aggregate of the developing countries so far reluctant to undertake climate action. From a modeling perspective, we treat each region as a homogenous macroeconomic aggregate. Let us collapse stages 2 to 4, which consecutively follow in time, to just one period so that we can suppress the time index in the notation. All variables are measured in per capita monetary values.

Each region, $r = \{n, s\}$, is characterized by its utility, U^r. Utility is a concave, increasing function of consumption, C^r. North and South have the same utility function U^r. Lower indexes indicate derivatives with respect to the corresponding variable throughout the paper.

$$U^r(C^r),\ U^r_{C^r} > 0,\ U^r_{C^rC^r} < 0 \tag{1}$$

Consumption is taken from output, Y^r, net of climate change damages, D^r, stemming from emissions, E^r (a by-product of production), and net of total investment in abatement (mitigation) of emissions, X^r. Let factor inputs be given as fixed endowments in each region for simplicity. Then output is also fixed and denoted by $Y^r = \bar{Y}^r$, where $\bar{(.)}$ indicates fixed variables (constants) throughout the paper. Output reductions with the aim to reduce emissions are included as non-technology-based abatement in X^r.

$$C^r = \bar{Y}^r - D^r - X^r \tag{2}$$

Damages are a convex, increasing function of the global stock of carbon in the atmosphere, a global public bad, denoted by E. We abstract from uncertainty in the magnitude of damages. One can think of damages as representing expected values.

$$D^r(E), \; D^r_E > 0, \; D^r_{EE} > 0 \tag{3}$$

$\bar{E}^0$ denotes cumulated initial emissions before the time frame of the game, and E^r denotes regional emissions within the time frame.

$$E = \bar{E}^0 + E^n + E^s \tag{4}$$

Investments X^r aim at the abatement of emissions stemming from production.

Abatement can be achieved via technology-based options denoted by T that are available in the North only. This assumption reflects the facts that most of the research and development is carried out within leading industrialized countries (c.f. SEI, 2006) and that the South-North technology gap is still large (c.f. World Bank, 2008). They require research and development for creating the technologies in the North, and technology transfer to transmit them from North to South. They require investment in capital to make them physically available. All these investments are subsumed under T. Note that we focus on emissions-saving technologies. This means that the benefit of using these technologies exclusively stems from the reduction in climate change damages. Let us now denote the technology options that the North uses within the North by T^{nn}, and North-South technology transfer by T^{ns}. The latter provides an option for the North to reduce emissions in the South at potentially lower marginal abatement costs.

Abatement can also be achieved via non-technology-based options within each region denoted by S. They include for example stricter management resulting in energy and emission-saving behavior and the reduction in output and as a consequence of emissions. We capture all this within S in form of additional costs. Non-technology options are available in both regions since they do not require advanced knowledge or skills. This means the South has the same capability as the North in terms of non-technology abatement options. We abstain from modeling non-technology-based transfers for abatement between regions since this is not a relevant issue in our analysis. This results in the following investments in abatement subsumed under X^r in each region.

$$X^n = S^{nn} + T^{nn} + T^{ns} \tag{5}$$

$$X^s = S^{ss} \tag{6}$$

The first superscript letter denotes the source that finances this abatement option, and the second superscript letter denotes the destination that implements the option. The outcome of these investments is given by the following relations that describe abatement options.

$$E^n(S^{nn}, T^{nn}),\ E^n_{(.)} < 0,\ E^n_{(.)(.)} > 0 \tag{7}$$

$$E^s(S^{ss}, T^{ns}),\ E^s_{(.)} < 0,\ E^s_{(.)(.)} > 0 \tag{8}$$

(.) denotes a derivative with respect to an argument of E. Let us treat the impact of North-South technology transfer, T^{ns}, on emissions, E^s, as an expected value, $EV(E^s_{T^{ns}}) < 0$, for the moment. These equations state that all investments reduce emissions, but with a diminishing marginal effect. This implies that abatement is subject to convex, increasing costs in each abatement option. Let us furthermore assume that raising all arguments by a factor f reduces emissions by a factor smaller than f. This implies that total abatement is also subject to convex, increasing costs. Let us further assume that not using one option does not raise total abatement costs to infinity. In other words, it is not essential to make use of all options. Hence, if one or more of the abatement options are not used or sub-optimally used, the costs of achieving the same emissions reduction will increase finitely. This happens because the marginal benefit of the remaining options will rise so that the remaining options will be used to a larger extent, and the diminishing marginal effect of the remaining options will reduce their effectiveness and raise total abatement costs.

Now the crucial point is that North-South technology transfer is subject to uncertainty per assumption. We assume two extreme cases for the marginal impact of the investment in North-South transfer T^{ns} on emissions denoting the successful outcome by (.):

$$E^s_{T^{ns}}(S^{ss}, T^{ns}) = \acute{E}^s_{T^{ns}}(S^{ss}, T^{ns}) < 0, \quad if\ success\ with\ probability\ \rho \tag{9}$$

$$E^s_{T^{ns}}(S^{ss}, T^{ns}) = 0, \quad if\ failure\ with\ probability\ (1-\rho) \tag{10}$$

Probability ρ is known to the players so that they can calculate expected values and make decisions based on these expected values. It follows for the *expected value* of the effect of investment in technology transfer:

$$EV(E^s_{T^{ns}}) = \rho \acute{E}^s_{T^{ns}} < 0 \tag{11}$$

3.3 Non-cooperation

Under non-cooperation, each region maximizes its utility given the abatement of the other region:

$$\max_{S^{nn}, T^{nn}, T^{ns}} U^n(\bar{Y}^n - D^n - X^n) \mid_{X^s} \tag{12}$$

$$\max_{S^{ss}} U^s(\bar{Y}^s - D^s - X^s) \mid_{X^n} \tag{13}$$

This results in a decentralized Nash equilibrium. Using Equations (3) to (8), we obtain the following first-order conditions that contain a condition for North-South technology transfer for the case of transfer success:

$$-D^n_E E^n_{S^{nn}} = -D^n_E E^n_{T^{nn}} = -D^n_E E^s_{T^{ns}} = -D^s_E E^s_{S^{ss}} = 1 \tag{14}$$

The non-cooperative solution is characterized by the equalization of marginal benefits of mitigation across regions and by the equalization of marginal emissions reductions for each type of investment within regions. The combination of both aspects yields the equalization of the marginal impact of all abatement options on region-specific climate change damage across both regions (= 1) as stated in the above optimality condition. Note that all derivatives $E^s_{(.)} < 0$ so that all expressions are positive. This solution states that the North will exploit each available mitigation option, not-technology-based and technology-based options at home and technology-based options abroad, to an optimal extent. The North can make use of 'cheap' abatement options in the South when the marginal mitigation costs are initially lower in the South than in the North. The South can only make use of non-technology-based options within the South. Due to the diminishing marginal benefit of investing in each option, an interior solution can be found. We recall that all mitigation options are interdependent so that the optimal use of one option depends on the optimal use of the other options.

In case of a transfer failure, the condition $-D^n_E E^s_{T^{ns}} = 1$ does not hold. According to (7) and (8) and the assumptions laid out below these equations, the initial marginal product of the remaining remaining options will then rise so that the remaining options will be used to a larger extend until the marginal benefits as given by the above equation are equalized.

Let the subscript $nco - su$ denote the non-cooperative solution in case of a transfer success, and $nco - fa$ the non-cooperative solution in case of a transfer failure. Then the non-cooperative solution can be characterized as:

$$\{U^r_{nco-su}, D^r_{nco-su}, E^r_{nco-su}, X^r_{nco-su}\}, \quad r = \{n, s\}, \quad if\ success\ with\ \rho \tag{15}$$

$$\{U^r_{nco-fa}, D^r_{nco-fa}, E^r_{nco-fa}, X^r_{nco-fa}\}, \quad r = \{n, s\}, \quad if\ failure\ with\ (1-\rho) \tag{16}$$

Let us assume that in case of a success, we find an interior solution in which all abatement options are used. It then follows from (7) and (8) and the assumptions laid out below these equations that in case of a failure, abatement will be less effective and thus more expensive (at the margin). Each player spends less on abatement so that emissions and as a consequence damages will be higher, and overall utility will be lower than in case of a success. We can therefore formulate the following straightforward Lemma:

Lemma 1. *Under non-cooperation, both regions are worse off in case of technology transfer failure than in case of transfer success.*

3.4 Cooperation

Under cooperation, a benevolent global planner maximizes the sum of utilities in both regions:

$$\max_{S^{nn},T^{nn},T^{ns},S^{ss}} [U^n(\bar{Y}^n - D^n - X^n) + U^s(\bar{Y}^s - D^s - X^s)] \tag{17}$$

This results in a centralized (social) global optimum. One can derive the first-order conditions in the same way as in the previous subsection using Equations (1) to (8). The new first-order conditions capture marginal damages of both regions instead of one region within each condition, consistent with the well-known Samuelson rule. They also take marginal utilities into account. This captures relative welfare of regions and thus per capita income, poverty and fairness. We obtain the following first-order conditions that contain a condition for North-South technology transfer for the case of transfer success:

$$\begin{aligned} -(D_E^n + \frac{U_C^s}{U_C^n} D_E^s) E_{S^{nn}}^n &= -(D_E^n + \frac{U_C^s}{U_C^n} D_E^s) E_{T^{nn}}^n \\ = -(D_E^n + \frac{U_C^s}{U_C^n} D_E^s) E_{T^{ns}}^s &= -(D_E^n + \frac{U_C^s}{U_C^n} D_E^s) E_{S^{ss}}^n = 1 \end{aligned} \tag{18}$$

The globally optimal solution results in the equalization of marginal emissions reductions $E_{(.)}^r$ since all emissions reductions are valued at the same marginal damage or marginal mitigation benefit $-(D_E^n + \frac{U_C^s}{U_C^n} D_E^s)$. (Note that again $E_{(.)}^s < 0$ so that all expressions are positive.) The Southern marginal damage will receive a relatively higher weight if its marginal utility is higher relative to the marginal utility of the North.

Let the subscript $co-su$ denote the cooperative solution in case of a transfer success, and $co-fa$ the non-cooperative solution in case of a transfer failure. Then the cooperative solution can be characterized as:

$$\{U_{co-su}^r, D_{co-su}^r, E_{co-su}^r, X_{co-su}^r\}, \quad r = \{n, s\}, \quad if\ success\ with\ \rho \tag{19}$$

$$\{U_{co-fa}^r, D_{co-fa}^r, E_{co-fa}^r, X_{co-fa}^r\}, \quad r = \{n, s\}, \quad if\ failure\ with\ (1-\rho) \tag{20}$$

Following the same argumentation as before, in case of a transfer failure, abatement will be less effective and thus more expensive (at the margin). Each player spends less on abatement so that emissions and damages will be higher, and overall utility will be lower.

Let us now presume that cooperation involves a binding agreement on emissions levels fixed at the optimal solution $\bar{E}_{co-su}^n$ and $\bar{E}_{co-su}^s$ in combination with a binding agreement on North-South technology transfer fixed at the optimal solution $\bar{T}_{co-su}^{ns}$, a component of X_{co-su}^n. Global and regional climate change damages are thus fixed at $\bar{D}_{co-su}^r = D_{co-fa}^r$. Then the situation does not change in case of a failure compared to a success for the North: The North has to pay $\bar{T}_{co-su}^{ns}$ in any case, and emissions and as a consequence climate change damages are fixed. A transfer failure on the contrary worsens the situation for the South: The South has to keep his emissions target $\bar{E}_{co-su}^s$ although the North's transfer $\bar{T}_{co-su}^{ns}$ has not created the expected emissions reduction. Since failure is due to 'Nature', the North who fulfilled the agreed transfer payment is not to be blamed for the failure. This confronts the South with the challenge of reaching the agreed (ambitious) emissions target without having advanced technologies available. This raises the South's mitigation costs beyond the level that is optimal from the South's point of view. Thus, we can formulate the following Lemma:

Lemma 2. *Under cooperation with a binding agreement on emissions and technology transfer, the South is worse off in case of technology transfer failure than in case of transfer success, while the North is equally well off in both cases.*

This means, technology transfer success is not an advantage compared to transfer failure for the North under cooperation. It is part of the cooperation agreement that makes both regions better of under ideal conditions, i.e., in the case of success.

3.5 Comparison

This section compares the cooperative with the non-cooperative solution.

Lemma 3. *For the scenario of technology transfer success, investments in abatement are higher, damages are lower, and global utility is higher under cooperation than under non-cooperation. The same is true for the scenario of technology transfer failure from a global point of view.*

The (ex-post) comparison of (18) with (14) shows that each type of abatement generates a higher marginal benefit under cooperation than under non-cooperation because the other region's marginal damage and utility are taken into account. As a consequence, all abatement options are exploited to a larger extent, and thus climate change damages will be lower. The joint utility maximization yields higher global welfare, defined as the sum of utility in the North and the South, than non-cooperation. This result is well-known. It applies for the scenario of success (Equations 15 and 19) and for the scenario of failure (16 and 20). However, it is ex-ante ambiguous whether transfer failure under cooperation or transfer success under non-cooperation is superior from a global point of view.

And it is not guaranteed that both regions are *individually* better off under cooperation than under non-cooperation, even in the success case. Suppose, the South has much higher marginal utility, marginal damage, and marginal emissions reduction per unit of investment in abatement than the North. Then it is possible that the North helps the South to such an extent that the North is worse off than under non-cooperation. Or the South receives insufficient technology transfer but has to fulfill much more stringent emissions targets under cooperation compared with non-cooperation because the South is the major carbon emitter and has low marginal abatement costs. Then the South can be individually worse off under cooperation than under non-cooperation. Let us thus introduce a budgetary (monetary) North-South transfer (that can be positive or negative) between the consumption (expenditure) budgets of the two regions denoted by R. R is chosen in such a way that both regions are better off under cooperation than under non-cooperation *given the ideal case that technology transfer succeeds.* Note that the first-order conditions for the optimal solution in (18) are not affected by R.

Lemma 4. *It exists a budgetary (monetary) ex-ante North-South transfer, R, that makes both regions better off under cooperation than under non-cooperation in case of technology transfer success.*

Cooperation generates higher global consumption and thus welfare than non-cooperation in case of a transfer success as stated by Lemma 3. It is hence possible to distribute the additional consumption value among the players via a transfer, R, such that both players are better off as stated by Lemma 4.

Since the North is equally well off in the case of a transfer failure than in the case of transfer success under cooperation according to Lemma 2, it also follows:

Lemma 5. *In case of technology transfer failure, the North is better off under cooperation than under non-cooperation.*

Nonetheless, even taking R into account, it is an open question whether the South is better off under cooperation than under non-cooperation in case of a *transfer failure:* On the one hand, under non-cooperation, the South has the advantage of not being bound to a certain emissions target. Therefore, the South chooses non-technology abatement, S^{ss}, such that it is optimal from its point of view, but not beyond that, as required by the emissions target under cooperation. Additionally, the South knows that once technology transfer fails, the North will raise non-technology investment, S^{nn}, in order to compensate for the failure. This is also beneficial for the South due to reduced global emissions. On the other hand, under cooperation, the North investments more in abatement because the North also takes Southern damages into account. Note that it is not clear, though not relevant here, whether the South is a net recipient of R. Thus, the South may have to pay or receive R additional to the loss under cooperation and technology transfer failure. Thus, we are arriving at a point where it is unclear whether a cooperative agreement of both regions can be achieved or not.

3.6 Solution

This subsection elaborates the comparison of utility levels in more detail. It then identifies aspects that increase the South's incentive to choose the non-cooperative solution and discusses policy options to increase these incentives.

The overall solution of the game hinges upon the players' decision upon cooperation or non-cooperation in stage 1. Players decide ex-ante by comparing expected utilities of both strategies. If the inequality holds, cooperation will be preferable:

$$\rho U^n_{co-su} + (1-\rho) U^n_{co-fa} \quad > \quad \rho U^n_{nco-su} + (1-\rho) U^n_{nco-fa} \tag{21}$$

$$\rho U^s_{co-su} + (1-\rho) U^s_{co-fa} \quad > \quad \rho U^s_{nco-su} + (1-\rho) U^s_{nco-fa} \tag{22}$$

These inequalities can be equivalently transformed into:

$$\rho(U^n_{co-su} - U^n_{nco-su}) + (1-\rho)(U^n_{co-fa} - U^n_{nco-fa}) \quad > \quad 0 \tag{23}$$

$$\rho(U^s_{co-su} - U^s_{nco-su}) + (1-\rho)(U^s_{co-fa} - U^s_{nco-fa}) \quad > \quad 0 \tag{24}$$

In the above equations, we compare cooperation to non-cooperation for each outcome of technology transfer. The considerations in the previous sections directly lead to the following result:

Proposition 1. *The North clearly prefers cooperation over non-cooperation ex ante.*

We know from Lemma 1, 2, 4 and 5 that $U^n_{co-fa} = U^n_{co-su} > U^n_{nco-su} > U^n_{nco-fa}$ in the presence of a transfer R. Thus, the North clearly prefers cooperation over non-cooperation. A crucial reason for this is that the cooperative agreement ensures the North against losses from a technology transfer failure. The South on the contrary has to pay the cost of a technology transfer failure.

What strategy is the South going to follow? In Equation (24) we know from Lemma 4 that $U^s_{co-su} > U^s_{nco-su}$ in the presence of a transfer R. We do not know in general whether $U^s_{co-fa} > U^s_{nco-fa}$ holds. Why? We recall that $U^s(\bar{Y}^s - D^s - S^{ss})$ is the South's objective. Which aspects are favorable for increasing the South's incentive to choose the cooperative solution given this objective? On the one hand, the optimality condition (18) shows that 'the North cares more for the South' when the Southern marginal utility is high relative to the Northern one and when the Southern marginal damage is high. This applies to the North's own abatement as well as to North-South technology transfer. On the other hand, higher marginal damages result in a more stringent emissions target (derived from Equation 18). Unfortunately from the South's point of view, such a stringent emissions target is also to be kept in case of a technology transfer failure. If North-South technology transfer has a strong impact on reducing abatement costs in the South, i.e. if $E^s_{T^{ns}}$ has initially a high magnitude and can thus achieve a substantial emissions reduction, the challenge will become tremendous in case of a transfer failure. This means, a stronger impact of technology transfer raises the gains in case of a success (higher U^s_{co-su}) but also the losses in case of a failure (lower U^s_{co-fa}) because it makes the emissions target to be achieved more stringent. Thus, the meaning of high Southern marginal damages is more ambiguous than pointed out in the literature so far. The meaning of a high Southern marginal utility is ambiguous too: It implies that the South is hit harder by a transfer failure that reduces consumption (lower U^s_{co-fa}) than the South can benefit from a transfer success that raises consumption (higher U^s_{co-su}). This is due to the diminishing marginal utility gained from higher consumption. In this sense, a stronger impact of technology transfer is a disadvantage because the losses in case of a failure receive a higher weight. (This effect is similar to that of risk aversion.) The meaning of the probability ρ for a transfer success is clear-cut though: A higher ρ puts more weight on the positive outcome of transfer success and thus favors the cooperative solution in (24) since $U^s_{co-su} > U^s_{nco-su}$.

Which aspects are favorable for the South's incentive to choose the non-cooperative solution? If marginal emissions reductions via technology transfer, denoted by $E^s_{T^{ns}}$ in Equation (14), are initially high, the North will strongly exploit this abatement option under non-cooperation in his own interest. This will also benefit the South. However, the South has nothing to lose compared to a world without technology transfer in case of a transfer failure under non-cooperation: The South has no binding emissions target to fulfill and is free to choose the abatement level which is optimal from his point of view. He could also choose the Southern abatement level given by the cooperative solution. This means, regarding Southern abatement itself, the South cannot be worse off than under cooperation. And in case of a transfer failure, the North will expand non-technology-based abatement in the North which also benefits the South. However, the North does not take Southern marginal damage and utility into account as in the cooperative solution when deciding upon his abatement. This is to the disadvantage of the South compared to cooperation. On the contrary, in case of a transfer failure the *North* suffers a tremendous loss: He has to pay T^{ns} ex-ante, without an effect on emissions ex-post. These considerations lead to the following lemma and proposition:

Lemma 6. *The cost of technology transfer failure is borne by the South under cooperation. It is borne by the North under non-cooperation.*

Thus, another argument for non-cooperative technology transfer is fairness or equity: If the South is the poor region with low consumption and high marginal utility, the

North, not the South, should bear the risk of a transfer failure. Based on mathematical arguments, a transfer failure reduces consumption, C, of the poor region to such a low level that marginal utility, U_C, becomes low with respect to the objective in (17) from a global point of view. We end up with the following proposition on the South's strategic choice:

Proposition 2. *The South's choice between cooperation and non-cooperation is ex-ante ambiguous. A higher probability of successful technology transfer makes cooperation more favorable for the South.*

This proposition follows from Lemma 1, 2 and 6, and the considerations above.

How can the South be convinced to choose cooperation? The first option is to adjust the monetary transfer R ex-post depending on the outcome of technology transfer. This could be directly realized in the form of an inter-governmental compensation payment. Or it could be realized via an insurance. In any case, it will be an additional North-South transfer. The question is whether cooperation is superior to non-cooperation within the *transfer failure* scenario from a global perspective so that *both* regions are better of after the transfer. This is according to Lemma 3 fulfilled. But cooperation in the failure case is not necessarily preferable to non-cooperation in the success case from a global point of view. Formally speaking, this requires a monetary North-South transfer R_{su} for the success case as assumed so far, and a different transfer R_{fa} for the failure case that compensates the South for its additional costs due to the failure. North and South then share the failure cost in a 'fair' way so that no region is worse off under cooperation and failure than under non-cooperation and failure. Equations (23) and (24) show that $U^r_{co-su} > U^r_{nco-su}$ and $U^r_{co-fa} > U^r_{nco-fa}$ are necessary and sufficient conditions for the superiority of cooperation for each region. It is according to (23) and (24) not necessary that each region is better off under cooperation failure than under non-cooperation success; i.e. $U^r_{co-fa} > U^r_{nco-su}$ is not required for the superiority of cooperation. This insurance or compensation solution is straightforward but nonetheless neglected in the political debate and the realization of technology funding. Let us also briefly discuss an alternative way of compensation: The North could also pay the compensation for the South *ex-ante* (within R) such that the South is *ex-ante* not only better off under cooperation than under non-cooperation for the success scenario, but also for the failure scenario so that Equation (24) is fulfilled. According to (22), this equivalent to a payment that is chosen such that the *expected value* of cooperation is higher than the expected value of non-cooperation for the South. This would solve the problem: Since globally $\sum_r [\rho U^r_{co-su} + (1-\rho) U^r_{co-fa}] >$

$\sum_r [\rho U^r_{nco-su} + (1-\rho) U^r_{nco-fa}]$, there will overall be an *expected* global utility gain of cooperation that can be distributed across the players to make both better off. But as long as the probability of success is relatively large, $\rho >> 0.5$, one will view transfer success as the likely, normal case, and transfer failure as the unlikely case to be insured. Thus we have the same situation as with an insurance; and no insurance would ever compensate for the damage before it actually happens since the damage probably will not occur. Therefore, the alternative way of compensation implies a compensation that is higher than necessary to achieve cooperation. Thus, the original option of adjusting the transfer in case of a transfer failure appears economically preferable. Nonetheless, any higher transfer could be agreed upon under normative South-North equity aspects. The challenge is in reality to separate the additional abatement costs that stem from a technology transfer failure from other kinds of additional costs that relate to the responsibility of one region or country. Governments have other interests than local politicians or firms that might might just seek short-term benefits or profits. This creates moral hazard and enforcement problems.

The second option is that under cooperation North and South agree on the *outcome of technology transfer* in terms of the emissions reduction to be achieved rather than on payments for technology transfer with an uncertain outcome. In recent climate negotiations the targets were formulated in monetary form, notably North-South transfers for mitigation amounting to 100 billion US-$ per year by 2020. Instead, the targets should be formulated in physical terms, for example mega-tons of carbon to be avoided, or giga-watts of wind power capacity to be installed. Such a definition of the outcomes of technology transfer avoids the risk that huge sums of money are paid with little effect on emissions. Formally speaking, the marginal Southern emissions reduction via technology transfer, $\bar{E}^s_{T^{ns}}$, derived from the success case given by Equation (18), and the implied total Southern emissions reduction, $\Delta_{T^{ns}} \bar{E}^s$, are agreed upon rather than the technology transfer payment, $\bar{T}^{ns}$, as part of X^n_{co-su} in Equation (19). The challenge is to measure and attribute the effects of technology transfer such as emissions savings correctly. It is for example easily possible to determine the total installed capacity of wind power plants. But the additional energy supply will enhance economic activity and increase complemental demand for fossil fuels. This creates a rebound effect. And it is questionable what the business as usual benchmark for emissions reductions is in reality. One will need to refer to (model) forecasts of emissions for the benchmark which involves uncertainty.

In summary, it follows from a theoretical point of view that there is doubt whether the South will agree to the cooperative solution. The ambiguity is created by the possibility of a technology transfer failure. This failure drives the overall outcome away from the globally optimal (and for each player optimal) outcome in case of a transfer success. Hence, a higher probability of transfer success brings the outcome statistically closer to the globally optimal outcome. An insurance against or compensation for technology transfer failure or an agreement on technology transfer in terms of the resulting emissions reductions can theoretically remedy the problem.

3.7 Empirics

Our theoretical considerations have highlighted the crucial role of international technology transfer in achieving cooperation in climate mitigation. Are these considerations practically relevant against the background of empirical facts? Can empirical facts fill the model parameters with a numerical meaning and help us find a clear result for the South's strategic choice? The following ten points confront our model with empirical observations:

(1) A high probability of technology transfer success would clearly make the cooperative solution more likely. Unfortunately, there is no data on technology funding available today. There will probably be more data in the future that will help us evaluate the effectiveness of technology funding schemes.

(2) The cooperative solution requires binding targets for emissions and volumes of technology transfer. Are emissions targets binding? Yes. An international emissions treaty naturally aims at binding targets and would include a kind of punishment mechanism for the case of non-compliance. (However, it is still possible that signatories do not comply like Canada regarding the Kyoto protocol.) Are there strictly binding, observable and enforceable agreements on technology transfer? So far, no. There are clean development and technology funding mechanisms existing (c.f. Climate Investment Funds, 2011; for an overview see Climate Funds Update, 2011), but the transfer volumes and particularly their outcomes are unclear. A binding agreement on volumes of North-South technology transfer in monetary terms is accordingly straightforward. But their practical realization is hardly enforceable, and their physical outcomes are hardly observable.

(3) The analysis of this paper is only relevant if global climate change damages are substantial in all model regions. If climate change damages occur mainly in one region, the cooperative solution will push the other region to care for this region with high damages. Will climate change damages be substantial for the North and the South? Yes. The Stern Review (2006), for instance, expects damages of up to ten percent of GDP within this century. Herein, the strongest damages are expected to occur in developing countries.

But damages are substantial in the industrialized countries too. Thus, the cooperative solution not only requires 'the North to care for the South', but also 'the South to care for the North'.

(4) The North will not only under cooperation but also under non-cooperation make use of emissions reductions in the South if the Southern emissions are substantial. Are the future emissions produced by the South extraordinarily high? Yes. According to IEA WEO (2011), non-OECD countries are expected to generate 2.4 times the emissions of OECD countries by 2035.

(5) The South might face high abatement costs, especially when advanced technologies are not available. This might create exceptionally high abatement cots in case of a technology transfer failure under cooperation. Are the investment volumes in mitigation necessary to avoid severe climate change damages substantial? Yes. IEA WEO (2011), for instance, estimates that cumulated investments in energy supply in the 450ppm scenario will amount to 2010-US$ 36.5 trillion from 2011 to 2035 (p. 224). Such investments appear in particular challenging for developing countries with low GDP.

(6) North-South transfers are particularly an issue when marginal abatement costs are lower in the South than in the North. Is this the case in reality? Yes. Developing countries usually have high energy and emissions intensities so that there is a high potential of cheap reduction options. Industrialized countries with low energy intensities such as Japan, on the contrary, have only a small potential of remaining emissions reduction options at high costs. Such 'reaping low-hanging fruits' in developing countries is also the main driver of the Clean Development Mechanism (CDM).

(7) Technology-based transfers are especially important if the North has technologies available that the South does not have. Do developing countries on average have low technological capabilities? Yes. For instance, in terms of the innovative capability, the 30 OECD countries contribute 82% of global R&D expenditures (US-$ 602 billion; SEI, 2006) in the year 2000. Moreover, some developing countries have made progress and caught up to industrialized countries in terms of technology levels, but the overall picture is mixed: The South-North technology gap is still large in many cases (c.f. World Bank, 2008).

(8) Our considerations attribute a substantial role to international technology transfers. Is it worthwhile discussing solutions that focus on technology transfer or is this issue negligible? The expected volumes of North-South transfer are also substantial, e.g. US-$ 100 billion annually by 2020 have been announced during the last climate conferences

(COPs). It is often not clear whether these transfers refer to mitigation, adaptation or both, if they are technology-related or not, and if they include monetary compensation for climate change damages. Notably, the expected climate damages are by far higher than the announced transfer, and the costs of mitigation and adaptation measures probably too (c.f. Stern, 2006; World Bank, 2010). This underlines the problem of uncertainty in the aim and the effects of the promised payments as examined in our paper. One crucial question is, however, whether decision makers in developing countries actually perceive future climate change related damages as a relevant for today's decisions – facing natural disasters, poverty, inequality, riots etc. today.

(9) Our considerations identify the difference in marginal utility between North and South as a crucial aspect in terms of global fairness. High marginal utility means low per capita income. Does the South have a lower (per capita) income than the North? Yes. While total GDP of OECD countries amounted to 2000-US$ 30.4 trillion in 2010, that of the other countries amounted to 2000-US$ 11.0 trillion only according to WDI (2012). Similarly, while GDP per capita in PPP (purchasing power parity) amounted on average to 2000-US$ 30.0 thousand in the OECD in 2010, the global average was 2000-US$ 9.8 thousand. This implies that negative income shocks such as those resulting from a technology transfer failure hit the South harder than the North. It stresses the importance of the issue of 'who bears the costs of a transfer failure'.

(10) Our considerations suggest that the uncertainty about the outcome of technology transfer makes the achievement of a cooperative solution more unlikely. Is this what we observe in reality? Yes, with regard to China as the most prominent example: China has concrete plans on improving energy efficiency and on testing locally restricted emissions trading schemes. It strongly exploits foreign technological knowledge via various channels (foreign direct investment and joint ventures in China, imports, imitation of products and processes, migration of Chinese students, Ph.D. students and workers etc.). But China is unwilling to sign a binding agreement on emissions – although knowing that countries like the EU or the USA would abate more so that China would be better off too. China seems to make sure that it first gets technologies and then goes for stringent energy and emissions reductions in order to avoid the technology transfer failure problem. Today technology funds are being realized, but without a binding agreement and without being conditional on keeping emissions targets. In other words, we do not observe issue linkage.

In summary, the empirical facts support the aspects that we scrutinized in our stylized model. Yet, they do not provide a clear-cut answer to the question whether the South will likely agree to the cooperative solution. Nonetheless, our theoretical consideration combined with the empirical facts cast serious doubt on the hypothesis that international technology transfer strengthens the stability of a cooperative climate coalition as often found in the literature. And this result is in accordance with what we observe in reality.

4 Conclusion

We have examined a stylized North-South model in a four-stage game. North and South can choose between cooperation (with a binding agreement on emissions and on the volume of North-South technology transfer) and non-cooperation (without any agreement). Our theoretical analysis shows that the risk of a North-South technology transfer makes it questionable that the South agrees to the cooperative solution. Technology transfer failure means that the technology-based North-South transfer payment in monetary terms does not achieve the expected, desired emissions reduction in physical terms. One crucial aspect is that the binding emissions target under cooperation insures the North against losses stemming from a technology transfer failure, while the South has to bear the cost of a transfer failure: The South has to expand his own abatement without having advanced Northern technologies available, which creates additional costs. This outcome is problematic under fairness and capability to pay aspects because the South is the poor region. Technology transfer does not only increase the benefit of being inside the climate coalition, but also of being outside and benefitting from technology transfer. As a new aspect, we argue that extended technology transfer tightens the emissions target of the South under cooperation which increases the pressure on the South in case of a technology transfer failure and makes cooperation less attractive. Otherwise, without uncertainty about the outcome of North-South technology transfer, the cooperative solution would be superior from a global point of view as well as from the North's and the South's point of view. Under non-cooperation, on the contrary, the North bears the cost of a transfer failure to a large extent: The transfer will be ineffective in the case of a transfer failure.

Is the risk of North-South technology transfer an obstacle to a cooperative climate change agreement? The answer is 'yes'. And this result is in line with reality: China, for example, makes use of international technology diffusion but is reluctant to sign a binding agreement on emissions although cooperation could make China better of.

How can the cooperative solution nevertheless be achieved? Our analysis highlights that simply strengthening international technology transfer does not suffice. Two policy solutions follow from our analysis: First, the South has to be insured against or compensated for additional abatement costs in case of a technology transfer failure. Second, when making use of issue linkage (in this case the combination of an emissions target with a technology transfer target), the technology transfer target should not only be formulated in monetary terms without clearly specifying the use and the aim of the funding, as the frequently mentioned 100 billion US-$ per year by 2020 for mitigation. It should also be formulated in physical terms, for example in form of installed capacity of renewable energy generators in gigawatt. This creates a direct link to actually realized emissions reductions and avoids the risk that huge sums of money are paid with little effect on emissions.

In our analysis, the asymmetry between countries having technologies for sure versus countries receiving technologies with uncertainty drives the results. This stylized analysis however has a narrow focus on technology transfer to developing countries. It neglects other aspects that are relevant for climate negotiations with developing countries such as per capita emissions and the historical responsibility for carbon stocks in the atmosphere. Moreover, our analysis neglects the heterogeneity among developing and emerging economies in terms of size, state of development, emissions intensity, culture etc. It does not examine specific technologies either. In this sense, appropriate policies need to be more specifically designed for countries and technologies. Future research could improve on these aspects. It could also take dynamics in terms of technical progress and technological catching up of the South into account.

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